Experiment Informed Methodology for Thermal Design of PM Machines

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Abstract—**The common approach used in the thermal design of electrical machines is calibrating thermal models based on the designer's previous experience, or hardware tests on a prototype machine. This allows for various manufacture and assembly nuances to be accounted for in the design process, assuring accurate and computationally efficient predictions of the machine thermal behaviour. The post-manufacture calibration of thermal models from tests on a complete machine has limited use in development of machine topologies, where no previous experience or machine hardware exist. In this context, an experiment informed design technique that makes use of reduced order machine sub-assemblies presents an attractive alternative. In particular, the hardware manufacture cost and time is significantly reduced compared to the prototyping of the complete machine assembly. This allows for numerous hardware samples to be constructed and tested, to inform the machine design process. The use of the machine sub-assembly testing is focused, but not limited to identifying and quantifying various power loss and heat transfer phenomena. This paper reviews the applicability of the sub-assembly testing in a broader context of the machine design. The aim of the research focuses on formulating a basis for sub-assembly based, experiment informed methodology for the thermal design of electrical machines.**

Keywords— **Design methodology, reduced-order machine sub-assembly; thermal analysis; PM electrical machine, hardware testing.**

I. Introduction

The continuous drive towards 'more electric' technologies and the subsequent need for high-performance electric machines calls for a more accurate and reliable thermal design-analysis, where various design, manufacture and assembly factors are accounted for at the initial stage of the design process. The wide ranges of built factors have significant impact on the machine's overall thermal behaviour and frequently require empirical techniques to validate the initial design assumptions [1]-[3]. In this context, testing methods that use the reduced-order machine subassemblies allow for a time and cost-effective derivation of various heat transfer coefficients and more in-depth analyses of power loss components are very desirable.

The development of these experimental techniques for a more accurate thermal study of electrical machines has recently gained more interest [4]-[44], with earlier work in the field focusing on custom built experimental setups, where more challenging heat transfer effects are investigated in detail, e.g. convective heat transfer analysis in the machine's mechanical air-gap between the rotor and stator assemblies [45]-[47]. It is important to note that the experimental test rigs used in the research emulate the machine's sub-assembly of interest in a simplified manner. In particular, the use of geometries that are easier to analyse theoretically, enables deriving more generic correlations applicable for a wider range of machine topologies.

The stator-winding assembly is usually attributed to the dominant power loss component within the machine body. There are numerous manufacturing and assembly processes affecting the stator-winding thermal behaviour and loss generated, making it particularly challenging to accurately analyse. The most recent work in the field treats the stator-winding assembly in detail [8]-[44]. Starting from tests on materials samples to evaluate the magnetic [48], mechanical [49]-[51] or thermal [4]-[17] characteristics for both homogeneous or composite materials, e.g. winding conductor, enamel and impregnation material or laminated core packs with insulating layer and adhesive liner between individual sheets, among others.

Following from material sample measurements are tests on stator-winding sectors, commonly referred to as motorettes. A motorette exemplar is usually constructed using representative materials and processes, i.e. conductor type, gauge and arrangement together with representative core pack, and electrical insulation system identical to the complete machine assembly. The motorette approach allows for significant reduction of manufacture cost and time, as compared with prototyping the complete machine. Results from tests on a number of motorettes constructed using alternative materials and processes allow for the initial design decisions regarding preferred manufacturing methods to be made. These results also inform thermal design-analysis providing more reliable and accurate machine's performance predictions [12]-[33]. The motorette testing is not limited to the heat transfer analysis [12]-[14], [18], [29] but also gives an insight into the loss generated in the stator-winding assembly. This is particularly important in the context of electric drive trains with a relatively high operating fundamental frequency, e.g. for the traction machines frequently meeting or exceeding 1 kHz [52]. The ac effects, both for the winding and core pack assemblies need to be carefully considered for such applications to provide a feasible low-loss design solution. The use of motorettes to investigate ageing of the complete winding insulation system has also been explored in the literature [53], [54].

Testing on a complete stator-winding assembly prior to the final machine assembly is the last stage of the sub-assembly testing, where various contact thermal resistances, power loss from interaction between neighbouring phases and repeatability of the manufacturing process used are of particular interest [32]-[37]. Some of the work reported in the literature refers here to insulation fault detection [4], [54], heat transfer from the stator-winding into the machine housing [40]-[44] and dummy rotor testing to estimate the mechanical loss contribution [55]. It is important to note that tests on the complete machine hardware still provide a vital source of information used in the machine development, where numerous designs variants are considered. The use of the subassembly testing is intended to supplement the design process, shortening the time from the initial design to the final hardware implementation, and providing a database for various built-factors.

This paper reviews the use of the sub-assembly testing approaches in thermal design-analysis, based on the available literature in the field and the authors' previous experience. The research effort is placed on defining a basis for sub-assembly based, experiment informed methodology for the thermal design of electrical machines.

II. EXPERIMENT INFORMED DESIGN METHODOLOGY

Despite increased interest in the machine sub-assembly testing, as a means of calibration for thermal design-analysis of electric machines [4]-[43], no generic experimental methodology has been defined yet. The research focus of this work is placed on formulating the basis for the sub-assembly experiment informed approach, in thermal design-analysis of PM machines. Fig.1 presents a flow diagram indicating the key steps for the proposed methodology, with photographs representing the selected material samples and machine sub-assemblies. The consecutive steps form building blocks of the methodology, details of which are reviewed and discussed in the following sections of the paper.

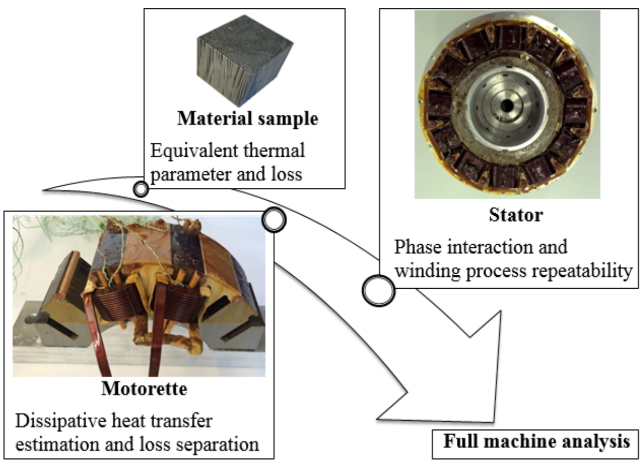

Fig. 1: Schematic flowchart of the proposed methodology.

A. Material Thermal Data

The first building step of the proposed methodology utilises tests on composite material samples, for the machine regions composed with multiple materials, e.g. impregnated winding [5]-[17] or laminated core pack assemblies [2], [13], [56]. In addition to providing accurate material thermal data, the material samples simplify and accelerate the thermal analysis through the use of homogenisation [6]-[17]. The principle of the homogenisation technique applied to the winding region is schematically shown in Fig. 2.

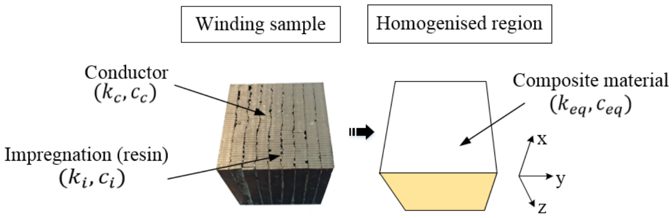

Fig. 2: Winding sample and equivalent homogenised region.

The equivalent thermal material data includes both the thermal conductivity and the specific heat capacitance. There are several empirical methods for measuring the thermal conductivity, e.g. the transient hot strip technique, the laser flash method or the heat flux meter approach [10]. The method employed in the proposed thermal design methodology makes use of the heat flux meter approach adopted to accommodate for the cuboidal samples [8]. The samples are also used for the measurement of the material equivalent specific heat capacitance using a calorimeter. The winding material sample testing is particularly useful in high fidelity thermal design-analysis, where the material thermal anisotropy and/or inhomogeneous power loss distribution is accounted for [7], [17]. These are particularly important in identification of the winding hot-spot. It is important to note that the thermal anisotropy is frequently neglected in thermal analysis of electrical machines where a lower resolution or coarse modelling approach is employed [1]-[3], [34]-[36], [57]-[59]. Fig. 3 presents examples of composite material samples for various winding conductor profiles and laminated core packs. Table I includes measured data revealing thermal anisotropy.

It is evident that the thermal conductivity along conductors (z-axis, Fig.3) is significantly larger than across the winding body (x- and y- axis, Fig.3). However, in most cases, the heat extraction path from the winding body is realised via the stator core-pack to the machine housing, therefore thermal conductivity in the x- and y- axes are particular important. In the case of the laminated core pack, the thermal conductivity is reduced across the laminated stack (z-axis, Fig. 3), as compared with within the individual lamination sheets (x- and y- axis, Fig. 3). This might be of consideration if a less common orientation or topology for the core assembly is envisaged [9]. Building a large number of material samples might not be feasible due to cost and time constraints, and alternative approaches making use of theoretical methods have been proposed in the literature [10], [11], [56], [60]. In particular, the analytical expressions for the estimation of the winding thermal conductivity, for various fill factors and materials design permutations, have been adapted to the conductor geometry, i.e. round [10], rectangular [11], and Litz wire [60]. It is important to note that these theoretical methods require nonetheless calibration, with experimental data derived from tests on the material samples [10].

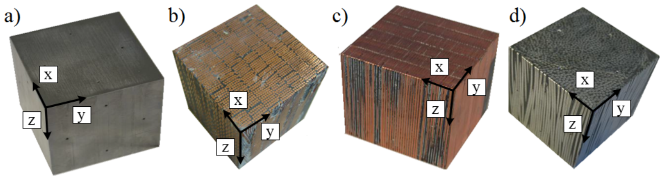

Fig.3: Material samples with rectangular profiled conductors, a) Silicon iron lamination bounded with cyanoacrylate, b) Type 8 16-AWG 14x14 Litz wire, c) Rectangular profiled 10×1.2 mm² copper wire with varnish impregnation, d) Round aluminium wire with epoxy impregnation.

TABLE 1: MEASURED SET OF THERMAL CONDUCTIVITIES FROM TESTS ON MATERIAL SAMPLES

Sample	K_x [W/mK]	K_y [W/mK]	K_z [W/mK]
a	22.2	22.1	4.9
b	2.2	5.1	253.0
c	1.9	3.1	331.2
d	2.4	2.3	151.0

Depending on the availability of hardware exemplars, a motorette, a stator or full machine assembly analysis is an alternative to material samples, when estimating thermal parameters associated with heat transfer from the winding body to stator core pack. Here, the use of appropriate winding model representation, e.g. equivalent material or layered model is required [11] in conjunction with experimental data. Such an approach is usually employed in thermal analysis using coarse and/or reduced order model definition [57], [58]. Testing on machine sub-assemblies is well suited when deriving the contact thermal resistance between the winding and stator sub-assemblies. However, this approach is less suitable for derivation of in-situ equivalent thermal properties for the winding region when instrumented in a conventional manner, i.e. a limited number of temperature sensors are used across the tested machine sub-assembly. This aspect of thermal model definition is discussed in detail, in the next section.

B. *Motorette assembly*

Once the individual material properties are derived, the global behaviour of the stator core pack and winding assembly is investigated. Testing on the motorette samples is selected as a second building block for the proposed methodology. The motorette approach allows for experimental derivation of numerous thermal parameters associated with materials and processes used in machine construction, e.g. impact of various insulation systems on heat extraction from the winding body into the machine periphery [12]-[14], and/or influence of the winding arrangement on the power loss generated [19]-[25]. Also, a number of heat extraction techniques using the motorette assemblies, e.g. natural convection, liquid cooling of the motor housing and direct oil cooling of the winding body has been shown in the literature [38]-[44]. Moreover, tests on motorette assemblies provide an insight into the power loss effects suitable in loss separation and also inform the loss temperature dependence, which is particularly important at ac operation, where the loss varies with temperature in a different manner to that at dc operation [33].

1) Thermal analysis: There are several examples of motorette assembly testing for the calibration of thermal models of electric machines in the literature [12]-[14], [18], [21]-[29]. Motorettes have been used for an in-situ analysis of thermal behaviour, accounting for interaction between various materials and sub-assemblies e.g. slot liner capability for absorbing impregnation material and its influence on the contact thermal resistance from the winding body to the stator core pack [12]-[14]. Also, the use of different insulation systems, e.g. impregnation and slot liner materials, together with alternative conductor materials have been investigated [14], [19]-[21]. It is important to note that tests on the complete machine assembly allow for the equivalent analysis to be conducted, but at higher expense when developing new machine designs, which would require a number of prototypes to be built. However, for in-volume manufacture of the existing design, thermal tests on machine samples provide quality assessment and data for development of future machine designs [1].

The winding body to stator core-pack, and stator core-pack to housing/frame contact interfaces are particularly challenging to predict theoretically, and are usually informed from appropriate experiments. The associated contact interface thermal resistance has a significant impact on the heat transfer from the winding into the machine periphery [1].

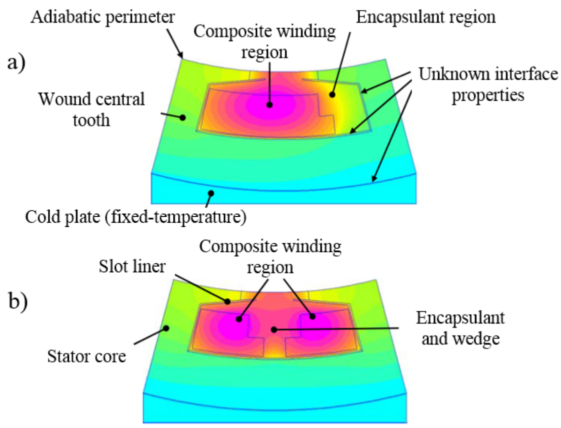

Fig. 4: 2D temperature plot from single-slot thermal FEA models. (a) 'Standard' winding, (b) ‘Slot-wedge’ winding, [22].

A common experimental method used in derivation of contact thermal resistances involves thermal testing with DC excitation and is applicable for all the stator/winding assemblies from the motorette to the complete machine. One of the techniques making use of motorette assemblies is designed to set a unidirectional heat path from the winding into the heatsink. The motorette under test is mounted on a temperature controlled cold-plate and placed in an insulated chamber. Such a setup is analogous to a machine with liquid cooled housing, however the technique is applicable to other types of machines. It is important to note that the heat transfer due to convection and radiation is usually assumed to be negligible, and heat extraction is realised by conduction only, allowing for the contact thermal resistances to be derived accurately [12]-[14].

Fig. 4 presents an example of a two-dimensional (2D) finite element (FE) thermal model of a motorette assembly, together with the boundary conditions. The interface between winding body and core pack is usually defined as an equivalent composite 'gap' region comprising the slot liner, impregnation and air cavities amalgam. Such an approach simplifies the model definition and reduces solving time, particularly when compared to using FE analysis. It is important to note that due to different conductor lay in the radial and circumferential directions, separate adjustments for both the heat transfer paths is frequently required, Fig.4.

Usually, the contact interface between motorette back iron and cold plate is not representative of that present in the complete machine assembly. This is related with manufacture and assembly processes used in housing the laminated stator core pack, e.g. heat shrunk stator into aluminium casing is used to provide 'good' heat transfer from the stator to machine housing. The contact force and surface finish between the stator and housing might be difficult to replicate for the motorette assembly, thus averaged values of the contact thermal resistance are available in the literature, or commercial software is frequently adopted [1], [51], [61]. Recent work in the field using a mock-up test setup with concentric cylinders has shown that the stator to housing thermal contact resistance is also affected by temperature related to the heat extraction technique from the machine housing [51].

The previous examples refer to active heat extraction from the machine housing using a liquid jacket. This method has been investigated in the literature via tests on a motorette assembly, for the evaluation of the influence of the liquid temperature and flow rate, as well as the derivation of the thermal contact resistance between the cooling structure and the stator back iron [41]-[44]. Also, there have been some developments in using motorette assemblies and/or mock-up experimental setups to provide some insight into heat extraction directly from the winding body by passing liquid. In order to simplify the hardware construction, heated pole pieces with identical shapes as the coils are used in some cases to replace the complete winding assembly [41]. Studies on this liquid cooling method mainly focus on the effects of the flow distribution and inlet temperature. Recent works into forced-air cooling investigate the air gap heat transfer in the context of disc type machines [38]-[40]. Traditionally, the heat transfer in the air gap is evaluated using dimensionless convection correlations obtained via tests on geometric mock-ups [45]-[47]. The current developments make use of geometrical mock-ups to investigate the effect of air gap size, flow rate and surface roughness, among others [38]-[40].

Motorettes have also been used to evaluate impact of different winding arrangements [20]-[28] and stator slot shapes [16] on the heat transfer effects. The motorette informed thermal design process has been found particularly useful when developing less common machine designs, where several design iterations are usually required to satisfy all the design requirements [18], [30]. However, some of the design alterations to improve heat transfer from the machine body also influence the machine electromagnetic behaviour, in particular the generated power loss. Therefore the loss analysis is vital in thermal design of electrical machines, and both the thermal and loss effects need to be evaluated concurrently due to their interdependence.

2) Power loss analysis: There are several examples illustrating the use of motorettes in power loss analysis with research focus placed on the winding loss contribution [15]-[32]. From one hand, the motorette testing is limited to some of the loss effects present in the complete machine, e.g. the effects associated with rotation of the PM rotor and/or interaction between winding phases are not accounted for. However, the measured loss data for such cases allows to identify the most promising design variants and informs the design process of the stator-winding assembly [20]-[32]. On the other hand, absence of some of the loss components present in the full machine allows for a simpler loss separation and provides better understanding of the loss effects. This is particularly important in the context of the ac loss effects, which require more careful considerations to identify the dominant ac effects.

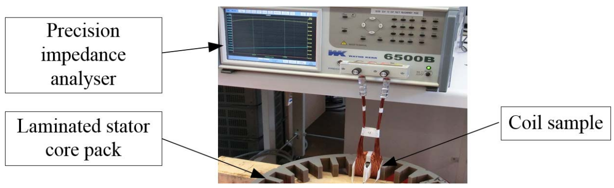

Fig. 5. Experimental setup used to evaluate ac excitation loss and winding inductance.

Despite developments made in the field of computational electromagnetics, ac winding loss prediction remains a challenging and time-consuming task. This results from the need for detailed loss data related with individual winding conductors. This is further exaggerated by the fact that for some of the winding arrangements the precise location of the individual conductors in the slot is unknown, e.g. multi-stranded mush winding [20]. In this context, tests on motorettes provide an alternative to the ac loss derivation/estimation, where functional representations of the winding and iron loss with frequency, temperature and magnitude of the excitation current are accounted for [20], [33]. Motorettes can also be used for the estimation of the end-winding ac loss contribution [15], [19]. The derivation of the end-winding ac loss usually requires the use of a 3D FE model, and experimental measurement appears as a fast and reliable alternative.

Experimental techniques used when analysing the ac winding power loss effects include direct power measurements and impedance analysis [17], [63]. In both cases, the motorette sample might be pre-heated at a selected temperature to account for the loss/temperature interdependency. Direct power measurement allows for more representative excitation of the tested sample, where the magnetic saturation can be accounted for. The impedance analysis can be used to access a wider frequency range, but with limited insight into the magnetic saturation effects due to the low amplitude of the excitation. For both methods, the separation of the iron loss from the total measured power loss is required. A FE model of the analysed motorette sample is usually utilised to derive the iron power loss component, which is subtracted from the total measured loss. The remaining power loss component is then assumed to be exclusively due to copper loss which allows for an accurate derivation of the winding ac power loss [13], [20], [25]. A scaling 'build factor' accounting for the core manufacture and assembly nuances, obtained for example from tests on a motorette assembly comprised of a known winding arrangement, can be used [20]. It is important to note that the degree of representability of the motorette assembly depends on the desired parameters. Ferrite material can, for example, replace laminated steel in order to ensure very low core losses in the considered frequency range so only the winding power loss is measured [51].

Other types of machine sub-assembly are illustrated in the literature to estimate the effects of ac current excitation, from non-representative core/winding assemblies such as pot-core coils for the estimation of the proximity effects [26], to the use of only two strands on a stator core to study the circulating current [29]. In particular, a number of studies measure the ac winding loss on a full stator core-pack, wound with a single tooth [17], [28], [29]. This option is particularly interesting when the core pack design is already definitive, but the winding configuration is still to be designated. For topologies with inherent magnetic and thermal isolation between phases, such as machines with single-layer modular windings, motorette assemblies can account for the majority of the ac winding loss due to excitation and thermal effects. For multi-layered topologies, motorettes comprised of several coils can be constructed to give some insights into the phase interaction, Fig.1 [23]. However, this is still not fully representative of the complete machine behaviour and tests on the complete stator assembly are usually preferred in this context.

C. *Stator assembly*

The stator assembly is chosen as a third building step of the methodology. The main advantage of tests on stator assembly is that it allows one to account for the interaction between phases. Dc tests are nonetheless frequently employed for the determination of the thermal parameters [33]-[37], for example in the context of material comparison [35], [36]. At first glance, building a full stator for the evaluation of the thermal parameters might seem both time-consuming and costly as compared with building a single-coil motorette assembly. However, tests on a stator assembly can be completed before the stator/rotor assemblage, and thus this building step does not necessary require building additional hardware exemplars. A further advantage of the use of a stator assembly instead of a motorette is that it provides insight on the repeatability of the manufacturing and/or assembly technique employed.

The stator assembly dc testing process includes the connection of the winding phases in series, with the temperature, current and voltage being recorded until steady-state is reached. The stator assembly might be analysed after assemblage with the housing frame structure, which allows for the evaluation of additional thermal parameters, such as the stator core/housing frame contact resistance and the convection and radiation heat transfer coefficients. A liquid-cooling structure can also be evaluated [37].

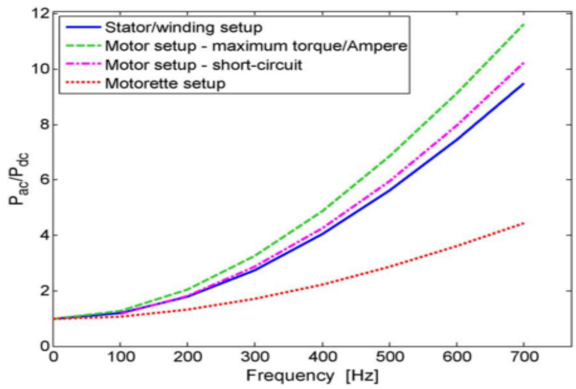

Fig. 6: Calculated P_{ac}/P_{dc} versus excitation frequency [33].

Tests on a stator assembly allows for the interaction between phases to be accounted for. Experimental approaches commonly involve ac tests with three-phase current excitation. The mean winding temperature is often manually controlled by applying an additional excitation current or placing the sample in a thermal chamber in-between test points, in order to get some insight into the temperature/loss interdependence [33], [34]. An insight into the ac power loss is obtained, and a comparison with FE results allows for an accurate calibration of the thermal and electromagnetic models. In particular, the end-winding loss contribution is not affected by the machine operating modes and therefore the stator/winding assembly is sufficient to find the machines overall end-winding loss component. Ac tests with one-phase excitation may be used in parallel, and the comparison between the results obtained from the three-phase analysis allows one to separate the bundle induced proximity loss from the strand-induced ones. In [33], the ratios of ac power loss to dc power loss obtained from FE for various excitation frequencies analysis are compared for motorette, complete stator and full machine models of a double-layer concentrated winding PM motor. In this case, the motorette estimates have a qualitative value only, and do not allow for the direct derivation of the full machine winding loss. Conversely, despite the absence of the rotor, the ac winding power loss derived from the stator assembly are closer to the one of the full motor assembly.

At the end of the design process, it is necessary to get some insight into the machines overall electromagnetic and mechanical loss, such as the ac effects due to the rotor rotation or the PM power loss. In this case, the complete machine assembly needs to be analysed. However, the stator assembly provides a comprehensive insight into the winding loss due to the current excitation.

III. CONCLUSION

There is a wide selection of experimental techniques used to supplement thermal design of electrical machines. The commonly used testing method makes use of a complete machine assembly. This provides a comprehensive insight into the heat transfers and power loss effects allowing for various manufacture and assembly nuances to be accounted for. In particular, all the electromagnetic and mechanical loss components are present. However, direct loss measurements from the complete machine assembly do not provide information regarding the loss share associated with individual machine regions. The loss separation is essential in thermal design of electrical machines, yet is challenging to be performed experimentally in a simple manner. Moreover, building numerous machine prototypes as a part of the design process is cost and time ineffective and alternative approaches utilising motorettes and machine sub-assemblies are gaining more interest.

In this paper, a foundation for a sub-assembly based, experiment informed methodology has been formulated as building steps. The consecutive steps, material samples, motorettes and stator assemblies, form building blocks of the methodology. The approach has been illustrated with numerous examples from the literature. The selected building steps of the methodology have been presented in comparison with the traditional machine testing methods, which highlighted both their respective limitations and applicability. Applicability of motorettes testing is wider than just for thermal and loss analysis and is illustrated in other contexts such as analysis of aging or electrical insulation. The research aim was to provide a fully informed process for thermal design of PM machines, allowing for the machine development effort to be reduced. This is particularly important in the context of less common machine designs for demanding applications. The majority of work has been focused on machine types where the majority of heat is conducted from the winding to the machine periphery. Machines with active heat extraction directly from the winding body have received less attention in the context of the motorette study. It is important to note, however, that despite the continuous research and recent findings in the domain of sub-assembly testing, further work is required to provide more definitive solutions concerning the motorette power loss analysis. The authors aim is to develop a more systematic approach by evaluating numerous examples from the material sample, through the motorette to the stator assembly.

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